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DESIGN STATUS AND APPLICATIONS OF SMALL REACTORS WITHOUT ON-SITE REFUELLING

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ABSTRACT

Small reactors without on-site refuelling (SRWORs) are the reactors that can operate without reloading and shuffling of fuel for a reasonably long period with no refuelling equipment being present in the reactor and no fuel being stored at the site during reactor operation. By virtue of being small, transportable and requiring no operations with fuel from a customer, such reactors form an attractive domain for fuel or even NPP leasing. SRWORs could simplify the implementation of safeguards and provide certain guarantees of sovereignty to those countries that would agree to forego the development of the indigenous fuel cycle. About 30 concepts of such reactors are being analyzed or developed in 6 IAEA member states.

Based on intermediate results of IAEA activities in support of the design and technology development for such reactors, the paper provides technical details on the design status, fuel cycle options and possible applications of SRWORs.

INTRODUCTION

Most NPPs to be deployed in the next decade are likely to be evolutionary designs building on proven systems while incorporating technological advances and often the economics of scale, resulting from the reactor outputs of up to 1600 MW(e). For the longer term, the focus is on innovative designs aiming to provide increased benefits not only economics and safety but also in proliferation resistance, security, waste management, and resource utilization (IAEA, 2005 and 2006a). Innovative NPPs target a variety of energy products, siting and fuel cycle options. Many innovative designs are reactors within the small-to-medium size range (Small and Medium Sized Reactors – SMRs), having an equivalent electric power less than 700 MW(e) or even less than 300 MW(e) [1]. More than 60 concepts and designs of innovative SMRs are under development in more than 15 IAEA Member States, both developed and developing countries. The projected timelines of readiness for prototype and commercial deployment are generally between 2010 and 2030. The above facts point to a renewed interest in Member States in the development and application of SMRs.

The attractive features of SMRs are:

- lower absolute overnight capital costs
- fitness for small electricity grids, the possibility to achieve reduced design complexity and reduced impact of human factors and, perhaps, reduced infrastructure and staff requirements – such reactors might be a good choice for many developing countries
- an option of incremental capacity increase (to meet the incremental increase of demand and to minimize financial risk) – a feature than may be attractive not only to developing countries
- an option of operation without on-site refuelling, which could offer certain benefits to those countries that would skip the development of an indigenous fuel cycle; and
- last but not least, SMRs are a preferred option for those non-electric applications that require a proximity to the customer, e.g., potable water production or district heating

In addition to the abovementioned, there is a growing concern that a "one-size-fits-all" approach will not be feasible for a evolving nuclear power, like it is not feasible in other

1. According to the classification adopted by IAEA, SMRs are reactors with the equivalent electric power below 700 MW, small reactors are reactors with the equivalent electric power of less than 300 MW

industries, e.g., car industry, aircraft industry, and energy production from fossil fuel, see Fig. 1.

A distinct trend of design and technology development for SMRs, accounting for about 50% of the overall number of SMR concepts and designs developed worldwide, is represented by the so-called small reactors without on-site refuelling (hereafter, SRWORs), also known as nuclear batteries, reactors with lifetime core operation, etc (IAEA, 2005). Small reactors without on-site refuelling (SRWORs) are the reactors designed for infrequent replacement of well-contained fuel cassette(s) in a manner that impedes clandestine diversion of nuclear fuel material.

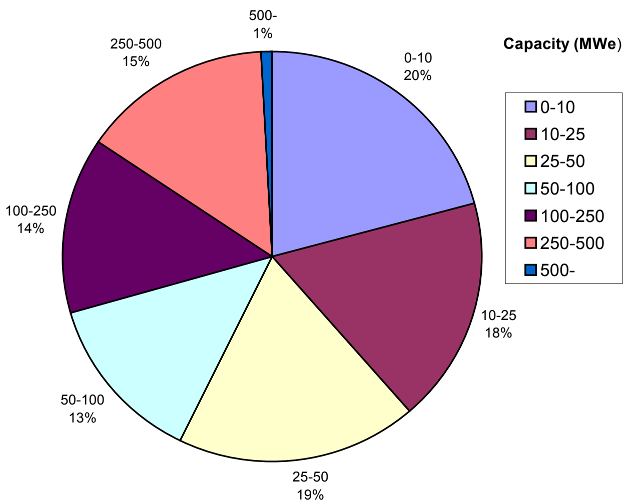

Figure 1. Distribution of unit capacity of power plants in Mexico in 2003, MW(e); *Minato and Wade (2005)*.

In addition to this, there may be a market for such reactors in remote areas with no electricity grids, often suffering from severe climate, unstable fossil fuel supplies and high cost of non-nuclear energy. Reflecting on these developments, the IAEA prepares a report on the status of designs of SRWORs, to be published this year, and also conducts a Coordinated Research Project (CRP) on development of such reactors. Based on the intermediate results of these activities, this paper provides an overview of the status of design and technology development for SRWORs.

DESIGN OBJECTIVES FOR SRWORs

Small reactors without on-site refuelling could be:

- factory fabricated and fuelled transportable reactors; or
- reactors with an infrequent whole-core reloading at a site performed by a special team that brings and takes away the core load and the refuelling equipment

Although it is still specified by many designers as a target, the key feature of SRWORs could be the absence of the refuelling equipment present during reactor operation in the reactor or at the site. Another key feature is that these reactor installations do not provide for fresh or spent fuel storage facilities at the site.

SRWORs incorporate increased refuelling interval (from 5 to 30 years and even more) consistent with plant economy and considerations of energy security. However, achieving an increased operation cycle is not a unique feature of the SRWORs, since similar development trend is observed for reactors with conventional refuelling schemes (such as refuelling in batches), including the ones of a large unit capacity.

The design goals for SRWORs as specified by their designers, *inter alia*, include:

- difficult unauthorized access to fuel
- design provisions to facilitate the implementation of safeguards
- capability to survive all postulated accident scenarios without requiring emergency response in the public domain, e.g., reduced or eliminated emergency planning zone (EPZ)
- economic competitiveness for anticipated market conditions and applications
- the capability to achieve higher manufacturing quality through factory production in series, design standardization and common basis for design certification; and
- flexibility of siting and applications

For reasons mentioned above, SRWORs provide an attractive domain for fuel or even NPP leasing. Specifically, such reactors reduce obligations of the user for spent fuel and waste management. Through adding a certain degree of independence on fuel supplier, SRWORs with a long operation cycle of 15-25 years could, perhaps, facilitate decisions of their users to skip the development of indigenous fuel cycles.

Many designs of such reactors provide for an operation with weld-sealed reactor vessel and remote monitoring, eliminate refuelling equipment and fuel storages at the site, and delegate all fuel handling operations to a special team; altogether, this could facilitate implementation of adequate safeguards in a scenario of expanded deployment of nuclear power.

TRENDS OF DESIGN AND TECHNOLOGY DEVELOPMENT

In most cases, long-life core operation without refuelling is achieved through a reduced core power density. In reactors with thermal neutron spectrum, burnable absorbers are effective to simplify reactivity control in lifetime core operation. In reactors with fast neutron spectrum, high conversion ratio in the reactor core is beneficial, which could be achieved by using dense nitride and metallic fuel, or by relying on a heterogeneous core arrangement with central fertile zone, increasing the importance of newly produced Pu.

As an exception, some advanced concepts of light water reactors relying on the use of the so-called micro fuel elements – coated particles with SiC or other outer coatings, which are in direct contact with water coolant, suggest that a principle of a 'sand glass' could be used to perform fuel shuffling and reloading operations inside the welded reactor vessel, see Fig. 2.

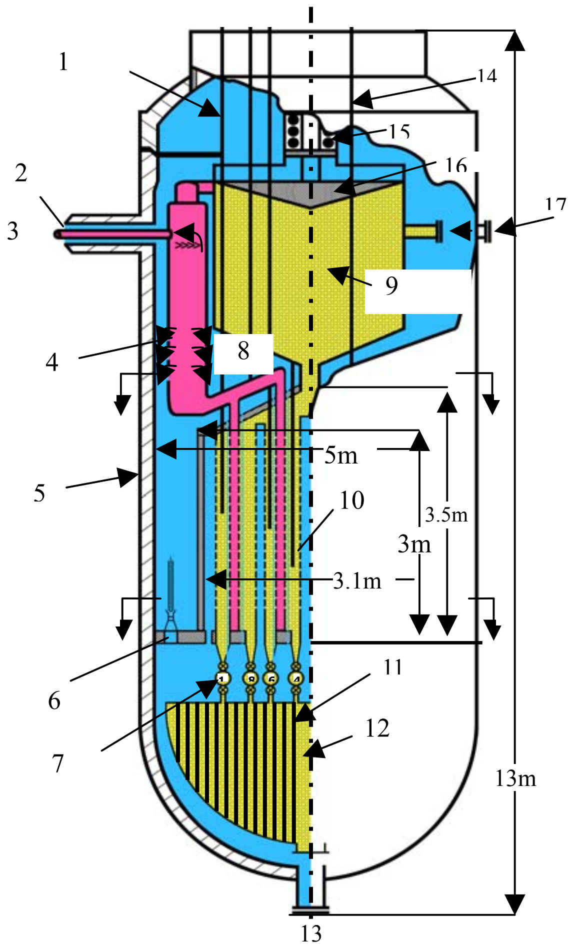

Figure 2. Concept of a 100 MW(e) reactor with a core lifetime of 40 years (AFPR-100, PNNL, USA): 1- scram rods; 2 – feedwater; 3 – steam to turbine; 4 – steam separator (8 units); 5 – RV; 6 – circulation pump; 7 – discharge valves; 8 – steam header; 9 – fresh fuel storage tank; 10 – pebble bed of micro fuel elements; 11 – borated steel pipes; 12 – spent fuel storage; 13 – spent fuel out; 14 – control rod; 15 – spring; 16 – piston; 17 – fresh fuel in; *Tsiklauri (2006)*.

Some of these concepts suggest that in this way a large capacity reactor without on-site refuelling could be developed. Several designs of SRWORs, such as the OKBM water cooled reactor designs and the SVBR-75/100 Pb-Bi design of IPPE and Gidropress (both from the Russian Federation), see Fig. 3 and Fig. 4 respectively, rely on a solid operation experience of shipboard and previous-generation submarine reactors, OKBM (2005) and Gromov (2002).

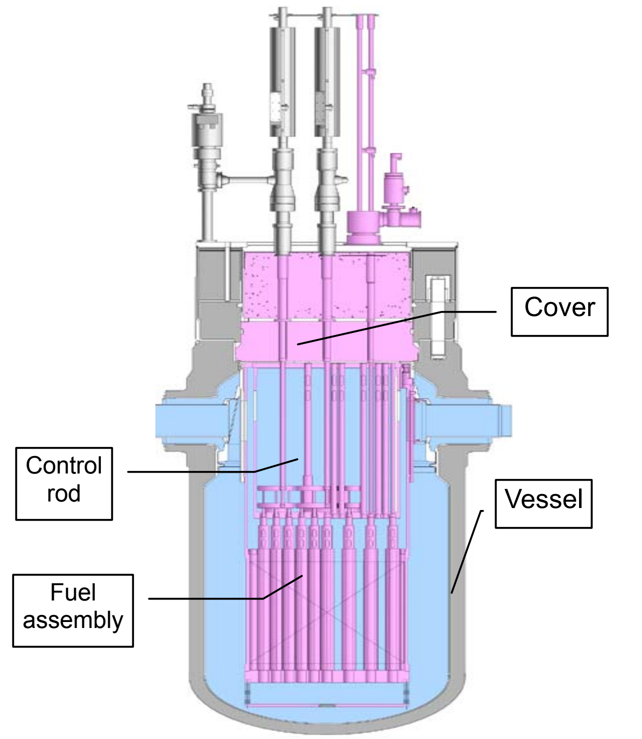

Figure 3. KLT-20 – a 25 MW(e) modification of the KLT-40S reactor, designed to achieve a core lifetime of 7-12 years in operation without on-site refuelling within a floating cogeneration plant, OKBM (Russian Federation); *OKBM (2005)*.

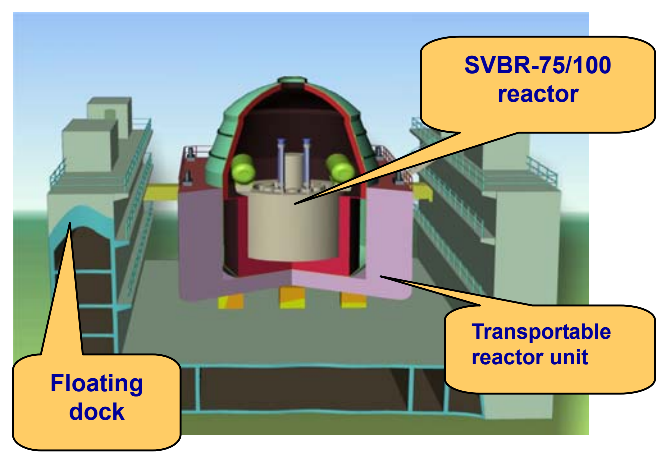

Figure 4. Floating dock with SVBR-75/100, a multipurpose lead-bismuth cooled reactor of 75 or 100 MW(e) developed by IPPE and "Gidropress" (Russian Federation), thoroughly backed by operating experience of previous-generation submarine reactors; *Gromov (2002)*.

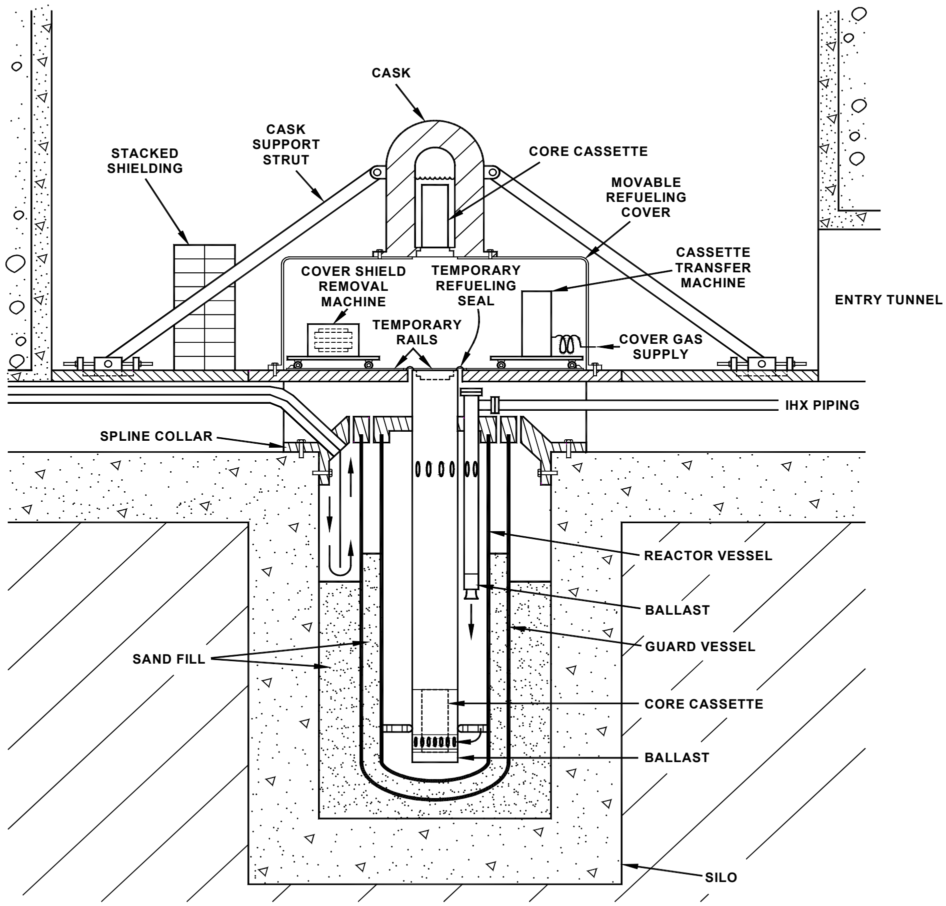

Figure 5. Whole core cassette refuelling using relocatable equipment from the regional centre as proposed for the STAR reactor family (USA), ***IAEA (2005)***

Many of them are being developed for both land-based and floating, e.g., barge-mounted NPPs and cogeneration plants.

Specifically, the SVBR-75/100 could be easily adjusted to many fuel cycles and provides for a non-nuclear safety grade balance of plant, which could be independently constructed and owned by the plant user. The reactor units can then be delivered and periodically replaced by the supplier, both by land and water, as shown in Fig. 4.

There are, however, certain differences in operation regimes between the marine propulsion and power reactors. The former tend to operate at full power only for short periods of time; for commercial NPPs the enrichment with ^{235}U shall not exceed 20%; and, last but not least, the operation cycle length of many SRWORs protrudes beyond the experience of the marine reactors, which is generally limited to 7-8 years of continuous operation.

Altogether, this puts forward a task of validation and testing of reactor safety and reliability for a long-life core operation under the new conditions.

To achieve SRWOR design targets, technologies of remote refuelling would need to be developed; and safety of spent fuel load/reactor transportation should be validated for short cooling periods after operation, see Fig. 5.

The economic competitiveness of SRWORs needs to be defined and proven for certain market conditions and certain markets. In some cases it may be diesels rather that combined cycle gas turbine plants with which such reactors would compete.

Regarding future energy systems, legal, institutional and infrastructure provisions for operation with regional fuel cycle centres should be elaborated, as discussed later in this paper.

It is also noted that floating, e.g., barge-mounted NPPs could be a good starting point to demonstrate SRWORs, IAEA (2005).

For both, multiple module plants to be used near big cities and individual modules for autonomous use in the remote areas, a simplification of plant design and operation resulting from strong reliance on the inherent and passive safety features and passive safety systems (passive safety design options) could be examined as being of potential benefit from the standpoints of economy and public acceptance. Because of a larger surface-to-volume ratio and smaller core power density, SRWORs create the prerequisites for expanded use of passive safety design options, such as safety-by-design approaches, e.g., integral designs of the primary coolant systems, optimum combinations of reactivity feedbacks, use of refractory fuel and structural materials, and incorporation of the reliable passive systems for core cooling and decay heat removal. For example, advanced structural materials for high temperature lead (lead-bismuth) coolant service and the use of coated particle type fuel in LWRs are mentioned as promising technology development trends for SRWORs, IAEA (2005).

The need to reduce the demerits of economy of scale is an objective of prime importance for all SRWORs. A near-term target for the majority of designs is to reduce or eliminate off-site emergency planning and associated incremental costs.

The flexibility in design, capacity and applications, as well as an option of incremental capacity increase provided by many designs are viewed as factors beneficial under the ongoing liberalization of energy markets. Last but not least, certain markets, e.g., remote and hard to access areas, may still benefit from energy production by SRWORs at a higher cost.

Stronger reliance on passive safety design options in SRWORs offers a possibility to achieve reduced design complexity and reduced demand of human interventions; however, the latter need to be proven and accepted by the regulator. Risk-informed approaches to safety qualification and plant licensing could help validate reduced design complexity and 'convert' it into lower capital and O&M costs, starting from reduced or eliminated off-site emergency planning. To achieve this, the reliability of passive safety systems needs to be quantified to incorporate them in PSA, to treat both active and passive systems in the same risk-informed way in relation to both, internal and external events, IAEA (2006b).

With passive safety systems, aspects like lack of data on some phenomena, missing operating experience over the wide range of conditions, and the smaller driving forces make the reliability evaluation of passive system *phenomena* a challenging task. Uncertainty and sensitivity analysis is identified important to quantify process condition reliability. Several methodologies to assess reliability of passive safety systems and incorporate them in PSA are being developed in at least four IAEA member states, e.g., as shown in Fig. 6

DESIGN STATUS AND APPLICATIONS

Of about 30 concepts and designs of such reactors developed worldwide, the majority is at a conceptual or even pre-conceptual design stage. The targeted dates for prototype deployment or commercialization range from ~2010 to ~2030.

More advanced development status is observed for the designs backed by experience of the relevant marine-reactor prototypes. (e.g., some OKBM designs of water cooled reactors and the SVBR-75/100 design of Pb-Bi cooled reactor from IPPE and Gidropress of Russia).

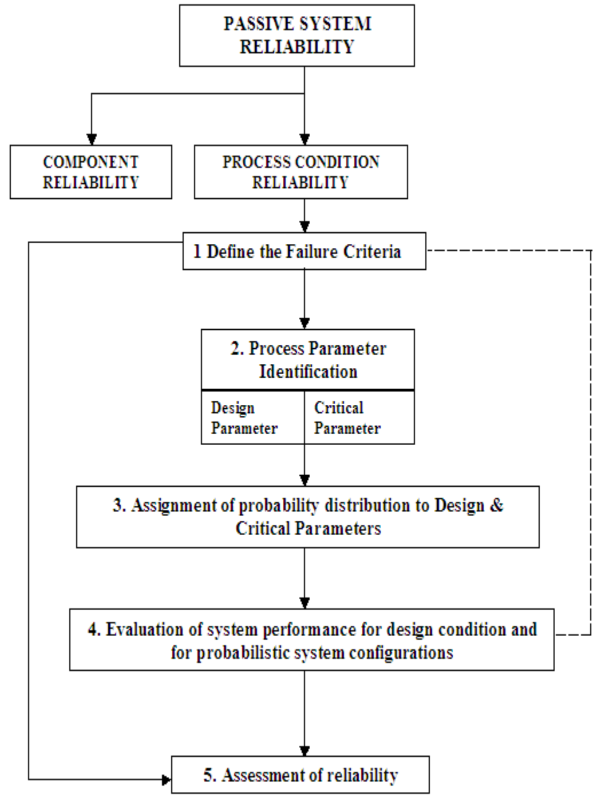

Figure 6. Passive system reliability evaluation methodology as being developed in BARC (India), *IAEA (2006b)*.

Certain progress was recently observed for the 4S sodium cooled reactor (Toshiba-CRIEPI, Japan), with a US NRC pre-application review possible in 2006, see Fig. 7. Small efforts with the support of the US DOE Generation-IV reactor programme are ongoing for SSTAR lead cooled reactor in the USA (Argonne National Laboratory).

A summary of the design status and projected applications for some of the reactors of this type is presented in Table 1. As it could be seen from the table, most SRWORs provide for multiple and often flexible cogeneration options.

PROVISIONS FOR CENTRALIZED FUEL CYCLE SERVICES

By virtue of being small, transportable and requiring no operations with fuel for a reasonably long period, SRWORs might provide an attractive domain for fuel or reactor installation leasing. The mere fact that a developing country that has purchased or leased such reactor could operate it for a long period without a fear of being put under pressure by the external vendor may facilitate an incentive to skip the development of the indigenous fuel cycle. Therefore, the proposers of SRWORs more often consider them in conjunction with centralized, probably, regional fuel cycle

Table 1. Design status and summary of selected SRWORs

Design name (**Capacity**, Designer, Country)	Reactor type; refuelling interval	Design stage[a]	Prototype deployment date[b]	Energy products[c]
Water cooled reactors				
VBER-150 (**110 MWe**, OKBM, Russia)	PWR, loop type; 8 years	C	2012 (floating NPP)	E, DH or PW
KLT-20 with long life core (**20 MWe**, OKBM, Russia)	PWR, loop type; 10 years	C	2011	E, DH or PW; EHS
ABV6 (**11 MWe**, OKBM, Russia)	PWR, integral type; 10-12 years	D	2012 (floating NPP) - 2013	E, DH or PW
PSRD (**31 MWe**, JAEA, Japan)	PWR, integral type, modular; 5 years	C	N/a	E
MASLWR (**35 MWe**, INL, U.S.A.)	PWR, integral type, modular; 5 years	C	N/a	E and PW
UNITHERM (**20 MWth**, RDIPE, Russia)	PWR, loop type; 20-25 years	C	~2010	E, DH, PW, PS
Sodium Cooled Reactors				
4S (**10-50 MWe**, Toshiba - CRIEPI, Japan)	Tank type, integral IHTS; ~30 years	C (completed)	After 2010	E, PW, H_2, O_2
BN GT-300/100 (**100 MWe**, IPPE, Russia)	Modular, railway transportable, no IHTS – gas turbine secondary circuit; 4.5 years	C	~2010	E and DH
RAPID (**1 MWe**, CRIEPI-MHI-JAEA, Japan)	Integral, pool type; 10 years	C	After 2007	E and PW
Lead-Bismuth Cooled Reactors				
SVBR-75/100 (**75-100 MWe**, IPPE-Gidropress, Russia)	Integral, pool type, modular; 6 - 9 years	B (completed)	2011-2013	E(RN), DH
ENHS (**125 MWth**, University of California, U.S.A.)	Integral, pool type; 15 years	FS (completed)	2020-2025	E, PW, DH, PS
Small sized LBFR (**50 MWe**, JAEA, Japan)	Tank type, integral; 30 years	C	N/a	E
Lead Cooled Reactors				
SSTAR (**20 MWe**, UCB, National Labs, U.S.A.)	Integral, pool type; 20 years	FS	2015	E, PW, DH
STAR-H2 (**400 MWth**, ANL, U.S.A.)	Integral, pool type; 20 years	FS	2025-2030	H_2, O_2 and PW (rejected heat)
Non-conventional designs				
MARS (**16 MWth**, RRC "Kurchatov Institute", Russia)	Pebble bed (fixed) fuel, molten salt coolant; 15-60 years	C (early stage)	~2015	E plus various non-electric applications
CHTR (**0.1 MWe**, BARC, India)	Prismatic HTGR type fuel, Pb-Bi coolant, VHTR	C	After ~2015	H_2 and E

(a) FS – feasibility study; C – conceptual design; B basic design; D – detailed design; L – license obtained
(b) Projections by designers, under favourable financing conditions
(c) E – electricity; PW – potable water; DH – district heating; H_2 – hydrogen production; EHS – emergency heat source for natural disaster regions; PS – process steam; RN – renovation of NPPs with decommissioned reactors

centres, perhaps, operated under an international control, IAEA (2005). It is also noted that such centres could, perhaps, start from international repositories of waste.

It is also noted that such centres could, perhaps, start from international repositories of waste.

Some examples of these proposals are given in Fig. 8 and Fig. 9.

The Russian proposal of a nuclear energy system with SRWORs and 'central repair and reloading bases' (IAEA, 2005) targets the poorly developed regions of the Far North and Far East of the country, where the supplies of fuel are complicated by unfavourable seasonal conditions and permanent frost, and the cost of a fossil energy is already ~5 times higher than in the rest of the country, see Fig. 8.

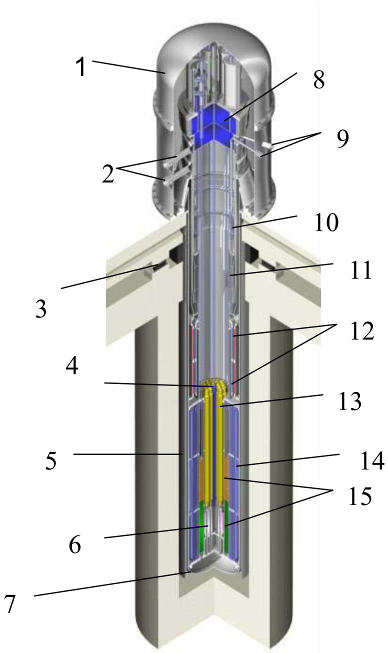

Figure 7. General view of the 4S reactor for a 50 MW(e) plant with 30-year core lifetime (Toshiba – CRIEPI, Japan): 1 – Top dome (containment vessel); 2 – Secondary sodium loop; 3 – Seismic isolator; 4 – Ultimate shutdown rod and fixed absorber; 5 – RVACS; 6 – Coolant inlet module; 7 – Reactor vessel and guard (containment) vessel; 8 – Shielding plug; 9 – Secondary sodium loop of PRACS (Passive Reactor Auxiliary Cooling System); 10 – Heat exchanger of PRACS; 11 – IHX; 12 – EM pumps; 13 – Fuel subassembly; 14 – Radial shielding; 15 – Movable reflector (6 sectors); *Toshiba (2005)*.

Another proposal, the 'hub-spoke' energy system with STAR reactors (ANL, USA), goes so far as to consider a global deployment scenario for battery-type reactors and regional fuel cycle centres targeting the eradication of poverty and supporting sustainable development worldwide. The 'hub-spoke' scenario shown in Fig. 9 attempts to segment the market for such reactors, i.e., to distribute the associated costs and risks between many private vendors. On the total, this might contribute to an improved overall competitiveness and deployment opportunity of such nuclear energy system.

The problem would then remain with the investment in the construction of regional fuel cycle centres, but the authors foresee that big oil and gas companies that might suffer the deficiency of fossil fuel resources at the time when such systems be ready for deployment could take a lead in this. Being centralized, the fuel cycle service centres that would also include fast reactors for fuel breeding (when necessary) and transmutation of waste will, in turn, benefit from the economy of scale.

INFRASTRUCTURE INNOVATIONS THAT COULD FACILITATE THE DEPLOYMENT OF SRWORs

To increase deployment opportunities for SMRs several infrastructure innovations might be helpful, such as:

- reciprocity of design certification and licensing agreements between countries
- legal frameworks for fuel and NPP leasing
- international regimes for trade in nuclear technology (national commitments to international norms on safety, operation, liability, etc.)
- multinational legal arrangements for fuel cycle centres (forego indigenous infrastructure in exchange for guaranteed access)

CONCLUSION

Small reactors without on-site refuelling (SRWORs) are the reactors designed for infrequent replacement of well-contained fuel cassette(s) in a manner that impedes clandestine diversion of nuclear fuel material.

About 30 concepts of such reactors are being analyzed or developed in the Russian Federation, USA, Japan, India, Brazil, and Indonesia. They cover different reactor lines: water cooled, sodium cooled, lead or lead bismuth cooled and molten salt cooled reactors. An increased refuelling interval could be achieved with reduced core power density, burnable absorbers, or high conversion ratio, as well some other approaches.

A targeted design feature of SRWORs is the absence of the refuelling equipment in the reactor or on the site during the whole period of a long operating cycle. Another key feature is that these reactor installations do not provide for fresh or spent fuel storage facilities at the site. SRWORs also incorporate increased refuelling interval (from 5 to 30 years and more) consistent with plant economy and considerations of energy security.

The potential benefits of SRWORs include:

- possibly lower construction costs in a dedicated facility in the supplier country
- lower investment costs and risks for the purchaser, especially if the reactor is leased rather than bought
- reduced obligations of the user for spent fuel and waste management; and
- possibly greater or easier non-proliferation assurances to the international community

An important benefit might also result from adding a certain degree of independence on fuel supplier; in this way SRWORs with a long refuelling interval could, perhaps, facilitate decisions of the user-countries to forego the development of the indigenous fuel cycles.

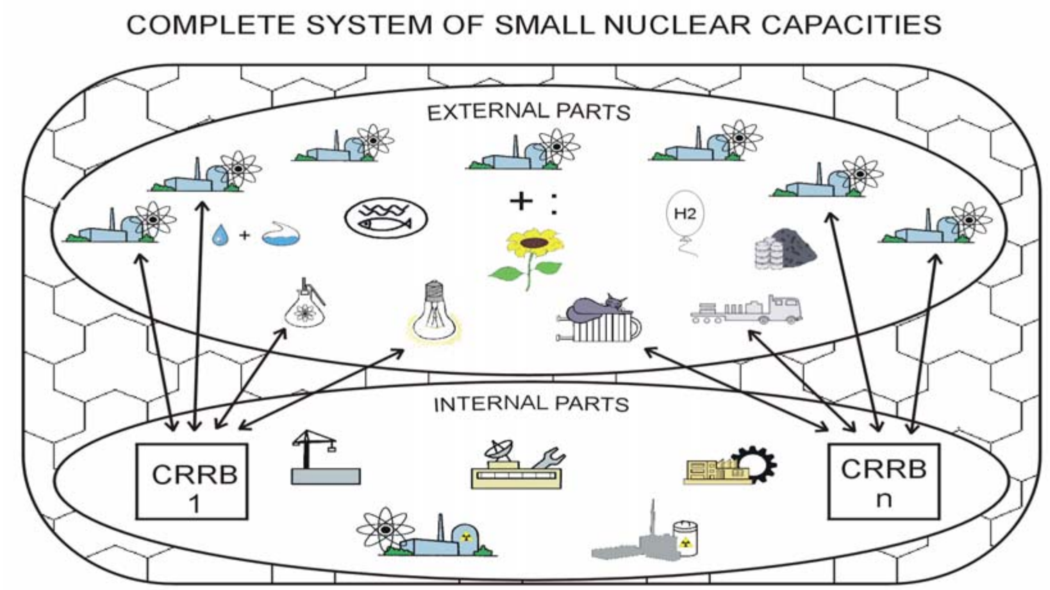

Figure 8. System of SRWORs with all repair, refuelling and maintenance operations, including the fuel cycle, being hidden from the outside world in the so-called "internal parts" of the system incorporating Central Repair and Refuelling Bases (CRRB) – a proposal from Russian Research Centre "Kurchatov Institute", *IAEA (2005)*.

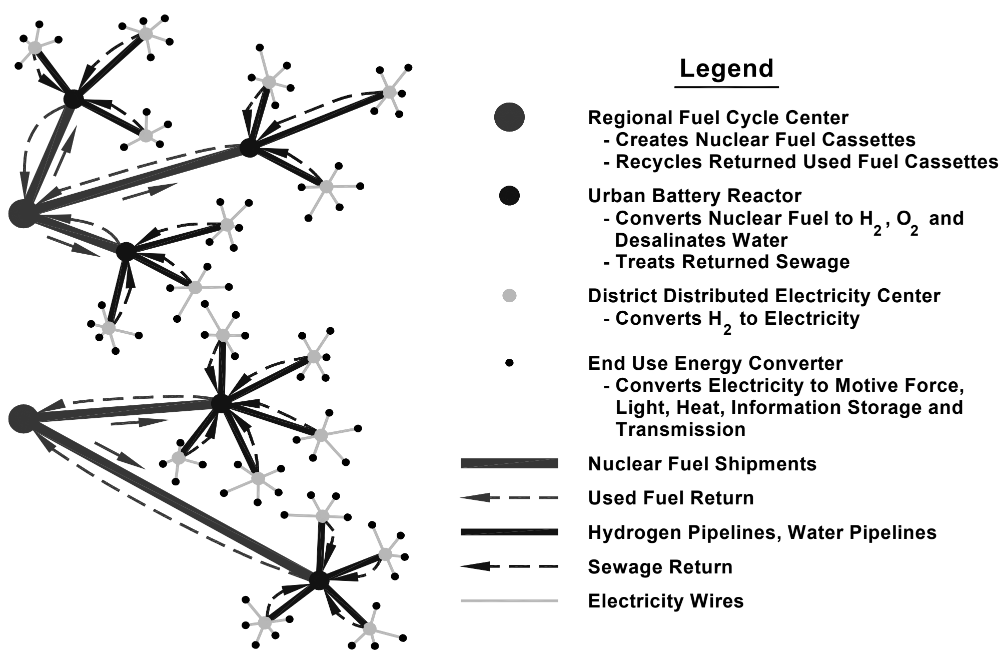

Figure 9. Hierarchical hub/spoke energy architecture (STAR reactor family, ANL (USA), *IAEA (2005)*.

Of about 30 concepts and designs of SRWORs developed worldwide, none has completed a detailed design stage and been licensed. The targeted deployment dates range from ~2010 to ~2030. More advanced development status is observed for the designs backed by experience of the marine propulsion reactors.

SRWORs have common technology development issues related to the validation of safety and reliability under long-life core operation, technology development for remote refuelling and provision of the adequate safety in transportation of reactor cores with spent nuclear fuel. Economic competitiveness of SRWORs for targeted market conditions and applications needs to be proven, and risk-informed approaches to safety qualification and licensing could be helpful to validate targeted design simplicity and communicate it to the regulators.

By virtue of being small, transportable and requiring no operations with fuel from a user, such reactors provide an attractive domain for fuel or reactor installation or NPP leasing. Therefore, the proposers of SRWORs often consider them in conjunction with centralized, perhaps, regional fuel cycle centres, probably, operated under an international control.

The establishment of legal frameworks for fuel and NPP leasing and multinational legal arrangements for fuel cycle centres (forego indigenous infrastructure in exchange for guaranteed access) are mentioned as infrastructure developments that could facilitate the deployment of SRWORs in many developing countries.

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